Fermilab/BD/TEV
Beams-doc-000-v1
October 28, 2003
Version 1.0

Tevatron Beam Position Monitor Upgrade Proton Signal Cancellation

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Abstract

The Tevatron BPM Upgrade Project will improve the current Tevatron BPM system, and part of the improvement will insure reliable pbar beam position measurements in the presence of protons. This paper discusses a method for de-embedding the proton signal that leaks through to the pbar end of the pickup and vice versa. The paper derives the linear relationship between the proton signal on the proton side of the pickup and the proton signal on the pbar side of the pickup for an ideal situation. It then discusses the effects of different non-idealities in the presence of real beam.

Table of Contents

History of this Document

Introduction

The Tevatron BPM Upgrade Project will improve the current Tevatron BPM system, and part of the improvement will insure reliable pbar beam position measurements in the presence of protons. There are currently two trains of thought on the best way to discern the pbar signal in the pickup without corruption from the proton signal.

One way is to time differentiate the signals in the pickup. At most of the BPM locations, there is some difference between the time that the pbars arrive in the pickup and when the protons arrive. With a large enough analog bandwidth, the signals from the different species can be sampled without cross interference. This places a very tight specification on the timing synchronization of the sample clock. It also excludes the measurement of pbars in locations where the bunches arrive simultaneously.

Another way to differentiate the signals in the pickup is with real-time de-embedding. The relationship between the proton signal on one end of the pickup and the proton signal at the isolated end of the pickup is well defined over a narrow bandwidth. Since the closed orbit information is contained in a narrow bandwidth, one can utilize the relationship by measuring the proton signal and using the information to remove the proton component of the measured pbar signal.

Linear Time-Invariance

The BPM system in the Tevatron is composed of passive components up to the digitizer input. These passive components consist of the transmission line plates in the detector, cables, attenuators, lumped element filters, etc. Passive components are by nature linear time-invariant. Linear time-invariance (LTI) is defined by the following properties[1]:

- Superposition – LTI systems have the property that when $v_{in}(t)$ produces $v_{out}(t)$ and $V_{in}(t)$ produces $V_{out}(t)$ then $a^* v_{in}(t) + b^* V_{in}(t)$ produces $a^* v_{out}(t) + b^* V_{out}(t)$, where a and b are complex constants.
- Time-invariance – LTI systems have the property that when $v_{in}(t)$ produces $v_{out}(t)$ then $v_{in}(t-\tau)$ produces $v_{out}(t-\tau)$.

Superposition implies that output signal can be separated into components due to independent input sources. LTI and superposition imply that exponentials are eigenfunctions of the system. This implies that signals with different frequency components do not mix inside the system.

S-Parameters

When doing closed orbit measurements (only measurement required for pbars and protons together), we are only interested in the power contained in a revolution harmonic of the beam rotation frequency. Because betatron and synchrotron oscillations can corrupt the closed orbit measurement, we are only interested in a very narrow bandwidth of information around the revolution harmonic (~10 Hz). If the response of the BPM

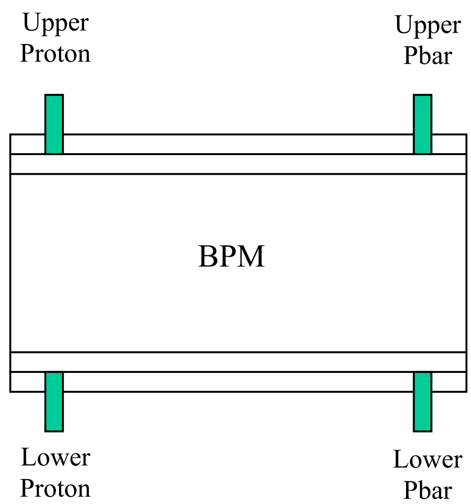

Figure 1: Block drawing of BPM hardware in the tunnel.

pickup, cables, and filter is relatively flat over the bandwidth of interest, then the total response of the system to some input can be approximated by a complex constant. These

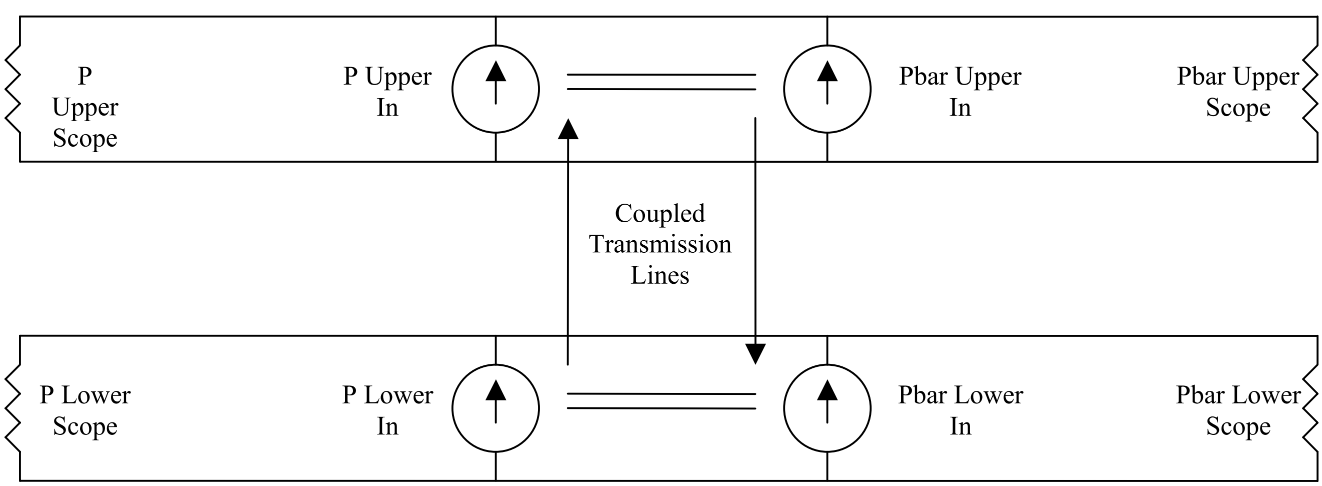

Figure 2: Simple transmission line model of BPM pickup and cables.

constants are a function of the frequency of the stimulus and do not vary with signal amplitude. A separate constant can also be defined for each independent stimulus of the system due to LTI of the system.

One of the standard methods for specifying the response of LTI systems is with S-parameters. S-parameters relate the signal at a particular output port of a LTI system with a particular input stimulus. The resultant relation matrix is a linear function of frequency ($V_{nout}(\omega) = S_{nk}(\omega)V_{kin}(\omega)$). Note that the input stimulus can be a source or a reflection from one of the output ports. The BPM hardware can be broken down into a simpler model for analysis with S-parameters. The beam acts as an ideal current source at the edges of the plates and the launches. The rest of the system consists of transmission lines, coupled transmission lines, and terminations.

The BPM hardware can be modeled as an eight-port LTI network. The input ports are the signals generated by the image current generated by the beam on the transmission

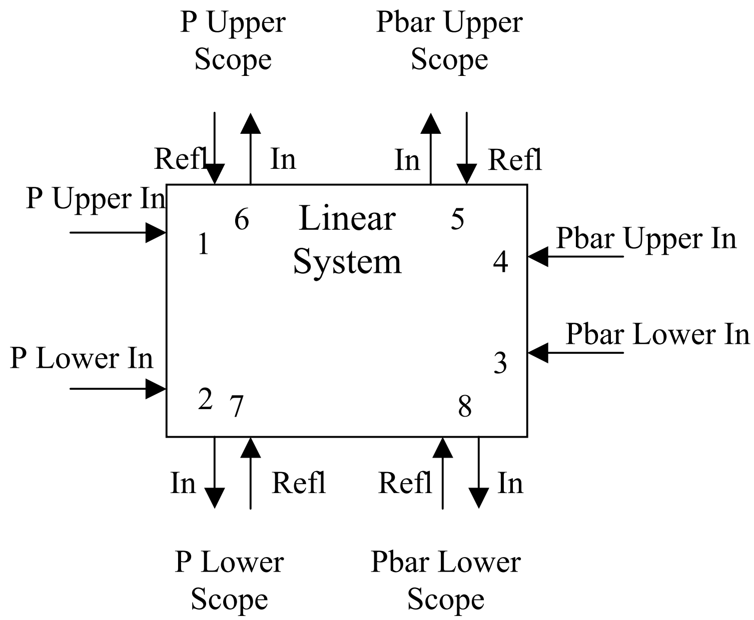

Figure 3: BPM hardware modeled as general eight-port network.

lines. The output ports are the ends of the cables in the service buildings connected to the BPM digitizers or a scope. The output ports also have input components that model the reflection off the terminations. Since the input ports are accurately modeled by ideal current sources, no power is coupled to the beam from the BPM, there is no output power term.

For the rest of the calculations, we assume that the BPM is symmetric in all three planes of reference. The calculations focus on the top plate only, but they are true for the bottom plate as well with a simple exercise of index manipulation. The upper plate output signals are described by:

$$V_{upbarout} = S_{51}V_{uprotin} + S_{52}V_{lprotin} + S_{53}V_{upbarin} + S_{54}V_{lpbarin} \tag{1}$$

$$V_{uprotout} = S_{61}V_{uprotin} + S_{62}V_{lprotin} + S_{63}V_{upbarin} + S_{64}V_{lpbarin} \tag{2}$$

Free space is also a passive, linear component to propagating electromagnetic fields. Therefore, the superposition law applies to fields from charges in a vacuum. The beam signal contains components from both protons and pbars. From the superposition law, the input components can be separated into pbar and proton contributions.

$$V_{xin} = V_{xin,prot} + V_{xin,pbar} \tag{3}$$

Ideal Conditions

In order to derive the equation for calibrating the proton signal on the pbar side of the pickup, we will assume certain ideal conditions. If the proton and pbar sources were fixed location transmitters inside the BPM instead of moving charges, then the entire system is LTI. Propagation of e-m fields through a vacuum is LTI. The coupling between the transmitters and the pickup plates is the only thing that needs to be defined. This coupling remains fixed, because it is a function of the distance between the transmitter and the plates.

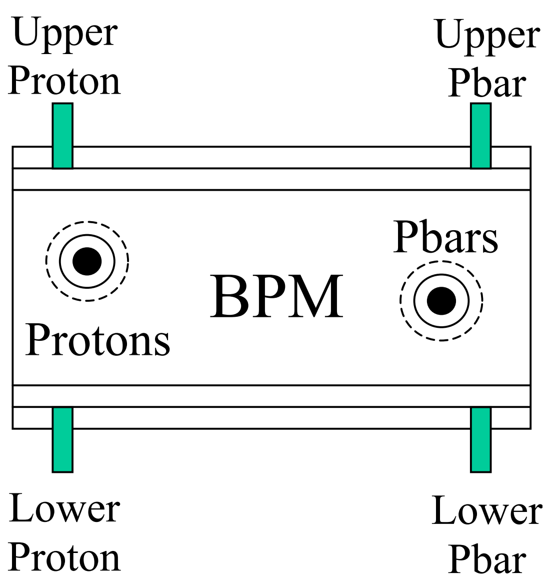

Figure 4: Illustration of ideal conditions with fixed transmitters in pickup.

$$\begin{gathered} V_{uprotin,prot} = k_1 I_{prot},\ V_{lprotin,prot} = k_2 I_{prot},\ V_{upbarin,prot} = k_3 I_{prot},\ V_{lpbarin,prot} = k_4 I_{prot} \\ V_{uprotin,pbar} = k_5 I_{pbar},\ V_{lprotin,pbar} = k_6 I_{pbar},\ V_{upbarin,prot} = k_7 I_{prot},\ V_{lpbarin,pbar} = k_8 I_{pbar} \end{gathered} \tag{4}$$

The new relationships for the outputs of the pickup become:

$$\begin{aligned} V_{upbarout} &= (S_{51}k_1 + S_{52}k_2 + S_{53}k_3 + S_{54}k_4)I_{prot} + (S_{51}k_5 + S_{52}k_6 + S_{53}k_7 + S_{54}k_8)I_{pbar} \\ V_{uprotout} &= (S_{61}k_1 + S_{62}k_2 + S_{63}k_3 + S_{64}k_4)I_{prot} + (S_{61}k_5 + S_{62}k_6 + S_{63}k_7 + S_{64}k_8)I_{pbar} \end{aligned} \tag{5}$$

Defining new variables:

$$V_{upbarout} = T_{pbar,prot} I_{prot} + T_{pbar,pbar} I_{pbar}$$
$$V_{uprotout} = T_{prot,prot} I_{prot} + T_{prot,pbar} I_{pbar} \tag{6}$$

For measurement of a single species, we are only interested in the output component associated with the species of interest. Solving for the pbar component at the pbar end of the pickup:

$$T_{pbar,pbar} I_{pbar} = \frac{V_{upbarout} - \dfrac{T_{pbar,prot}}{T_{prot,prot}} V_{uprotout}}{1 - \dfrac{T_{pbar,prot} T_{prot,pbar}}{T_{pbar,pbar} T_{prot,prot}}} \tag{7}$$

We make a change in variables noting that the ratio of transfer matrix terms is just the ratio of the output signals measured with only one species of beam in the machine. The denominator contains a term that is the product of the cross transfer functions, which is proportional to the directivity squared.

$$V_{upbarout,pbar} = \frac{V_{upbarout} - \dfrac{V_{upbarout,prot}}{V_{uprtotout,prot}} V_{uprotout}}{1 - directivity^2} \tag{8}$$

$$V_{uprotout,prot} = \frac{V_{uprotout} - \dfrac{V_{uprotout,pbar}}{V_{upbarout,pbar}} V_{upbarout}}{1 - directivity^2} \tag{9}$$

These two equations explain how the pbar signal from the pbar pickup is isolated from the proton signal and vice versa. Signal is measured simultaneously from the proton end of the BPM and the pbar end. The signal from the proton end of the pickup is multiplied by a calibration ratio derived from measuring both ends with protons only. This result is subtracted from the measured signal from the pbar end to leave only the pbar component of the signal.

Non-idealities

The key to this technique is that the calibration ratio must be constant for all beam conditions. The only thing that should change the calibration ratio is changes to the physical hardware (thermal expansion, etc.). With the conditions described above where there are two fixed transmitters in the detector, the calibration ratio stays constant for any physical geometry. However, the beam location is not fixed, and the signal coupled into the detector from the beam is not time invariant or a linear function of position. The expansion of the calibration ratio is:

$$\frac{V_{upbarout,prot}}{V_{uprotout,prot}} = \frac{S_{51}k_1 + S_{52}k_2 + S_{53}k_3 + S_{54}k_4}{S_{61}k_1 + S_{62}k_2 + S_{63}k_3 + S_{64}k_4} \tag{10}$$

One simplification of the ratio is the fact that the signal coupled to the pbar port is the same amplitude as the signal coupled to the proton port. There is only a sign change and a delay across the length of the plates.

$$k_4 = -k_1 e^{-j\theta}, \; k_3 = -k_2 e^{-j\theta} \tag{11}$$

$$\frac{V_{upbarout,prot}}{V_{uprotout,prot}} = \frac{(S_{51} - S_{54}e^{-j\theta})k_1 + (S_{52} - S_{53}e^{-j\theta})k_2}{(S_{61} - S_{64}e^{-j\theta})k_1 + (S_{62} - S_{63}e^{-j\theta})k_2} \tag{12}$$

The left side of the ratio above represents the beam signal that is directly coupled to the top plate. The right side of the ratio represents the signal that is coupled from the bottom plate to the top plate. If there was no coupling, the calibration ratio would remain fixed for all beam positions (or all values of k_1). With coupling, however, there is the possibility of the ratio being corrupted by the imbalance between k_1 and k_2.

The coupling coefficient is a function only of the pickup geometry, and it doesn't change as a function of beam position. I will assume that this coefficient is constant over the distance of the pickup and that the amplitude of the coupled signal back to the source is negligible. The signal generated on the coupled plate is proportional to the total current launched down the source plate. If the BPM pickup is perfectly symmetrical in the z-plane, the amplitude of the current launched on the pickup plate from a current source on one end of the pickup will equal the amplitude from a current source on the other side of the plate. Let the product of the current launched down the source plate and the coupling be A.

$$S_{n1} = A * S_{n2}, \; S_{n4} = A * S_{n3} \tag{13}$$

$$\frac{V_{upbarout,prot}}{V_{uprotout,prot}} = \frac{(S_{51} - S_{54}e^{-j\theta})(k_1 + Ak_2)}{(S_{61} - S_{64}e^{-j\theta})(k_1 + Ak_2)} \tag{14}$$

The above expression shows that for ideal symmetry, the calibration ratio remains unchanged in the presence of coupling. Unfortunately, the symmetry is not perfect. The upstream and downstream ports see slightly different termination impedances, and this will have a small effect on the calibration ratio.

Another non-ideality that spoils the scheme is beam that goes into the BPM off angle. However, the maximum angle for the vast majority of locations in the Tev lattice is about 200μR. This corresponds to a total offset of about 40μm from one end of the BPM to the other. This is well below the 100μm resolution for pbars specified in the requirements.

References

[1] Circuits, Signals, and Systems, W. Siebert, The MIT Press, Cambridge, MA, 1986.